

# Direct welding of fused silica with femtosecond fiber laser

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## ABSTRACT

Development of techniques for joining and welding materials on a micrometer scale is of great importance in a number of applications, including life science, sensing, optoelectronics and MEMS packaging. In this paper, methods of welding and sealing optically transparent materials using a femtosecond fiber laser (1 MHz & 1  $\mu\text{m}$ ) were demonstrated which overcome the limit of small area welding of optical materials from previous work. When fs laser pulses are tightly focused at the interface of the materials, localized heat accumulation based on nonlinear absorption and quenching occur around the focal volume, which melts and resolidifies, thus welds the materials without inserting an intermediate layer. The welding process does not need any preprocessing before the welding. At first, single line welding results with different laser parameters was studied. Then successful bonding between fused silica with multi line scanning method was introduced. Finally, complete sealing of transparent materials with fs laser was demonstrated. Scanning electron microscopy (SEM) images of the sample prove successful welding without voids or cracks. This laser micro-welding technique can be extended to welding of semiconductor materials and has potential for various applications, such as optoelectronic devices and MEMS system.

**Keywords:** Femtosecond laser, fiber laser, transparent material, welding, sealing.

## 1. INTRODUCTION

Recently, femtosecond (fs) laser direct writing of transparent material has become a powerful micro-fabrication technique for photonic devices [1-5]. Compared with traditional fabrication technique, fs laser waveguide writing has a number of advantages – simple, cost effective and capability of wide variety of material processing and “at will” structure writing. In addition, fs laser pulses give the potential to directly write structures inside transparent materials which are impossible with traditional continuous wave or long pulsed lasers. When the fs laser pulses are tightly focused inside a bulk of transparent material, the high intensity inside the focal volume will induce multi-photon or tunneling ionization and subsequent avalanche ionization occurs [6], and finally this nonlinear absorption results in the creation of hot plasma and subsequent heating to the surrounding materials. Therefore, the fs laser can act as a local heat source in the volume and lead to melting of the materials. The melting and quenching of the material result in the generation of covalent bonds if the laser focus is located at the interface between two adjacent samples. This can be used for joining and welding of optical transparent materials for many applications, such as life science, sensing, optoelectronics and MEMS packaging.

Current joining methods developed with specific properties have limited application. Joining technologies such as binding or gluing using adhesives suffer from mismatch between the thermal expansion coefficients of material and the adhesive, and the long term stability of the bonds [7]. Oxygen and moisture gradually penetrate the interior of the component and affect its function. Optical contact bonding the most common bonding technique for glasses, which is a glueless process whereby two closely conformal surfaces are joined together, being held purely by intermolecular forces. But this adhesive-free process need ultra flat and ultra clean surfaces with the same curvature [8]. Furthermore the bond strength is typically very weak (a few kPa) and is highly susceptible to impact load. Laser welding using Continuous Wave (CW) lasers or long pulsed lasers has problem of crack development during cooling period [9-10]. Moreover, since it is based on linear absorption, it requires one of the samples to be joined be transparent and the other sample to be absorbing at the wavelength of the lasers used. The selection of materials to be joined is limited and it cannot be carried out for non-absorbing materials such as glasses.

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Many researchers have demonstrated successful welding of transparent materials using fs lasers for both similar materials [11-16] and dissimilar materials [17-18]. Fs laser welding allows space-selective welding without inserting intermediate layers and the highly localized heat generation minimizes the thermal induced stress and can effectively suppress the development of the thermally induced cracks. It is also shown that high repetition rate laser systems operating in the MHz range can lead to the enlarged modification region due to heat accumulation of successive pulses. However, these researches only achieve good welding between substrates and components with small area and limit the applicability of this technique to only small components.

In this paper, the local modification of fs fiber laser (1  $\mu\text{m}$  wavelength & 750 fs pulse duration) radiation inside fused silica was investigated firstly with single line scanning. Secondly, two fused silica substrates were joined together and the welding zones were checked and characterized for both single line and multi line scanning cases. By using fs laser welding technology, we also demonstrated complete four-edge sealing of two fused silica substrates and the bond is free from impurities, chemical contaminants and premature aging which are typical of the use of adhesives. This greatly increases the potential for fs laser welding applications in semiconductor industry, precision optic manufacturing and aerospace engineering.

## 2. METHODS & MATERIALS

### 2.1 Experimental setup

Welding of fused silica was achieved by focusing high repetition rate fs laser radiation within two substrates and moving substrates relative to the laser focus position parallel to the interface. Figure 1 shows the sketch of the fs laser welding experimental set up. A commercialized mode-locked fiber laser manufactured by PolarOnyx, Inc. was used. The output beam is typically Gaussian shape with pulse duration of 750 fs and a spectral bandwidth centered at 1  $\mu\text{m}$ . The pulse repetition rate can be adjusted between 1 Hz and 1 MHz with the help of an acousto-optic modulator (AOM). The maximum output pulse energy is 10  $\mu\text{J}$ . In all the experiments, the laser beam was guided by mirrors and was focused by an objective lens towards the sample on the sample fixture and welding seams were generated when moving the substrate. The focal spot size ( $D$ ) for the laser beam can be calculated by the diffraction limit, as shown by Eq. (1):

$$D = 1.22 \frac{\lambda}{N.A.} \quad (1)$$

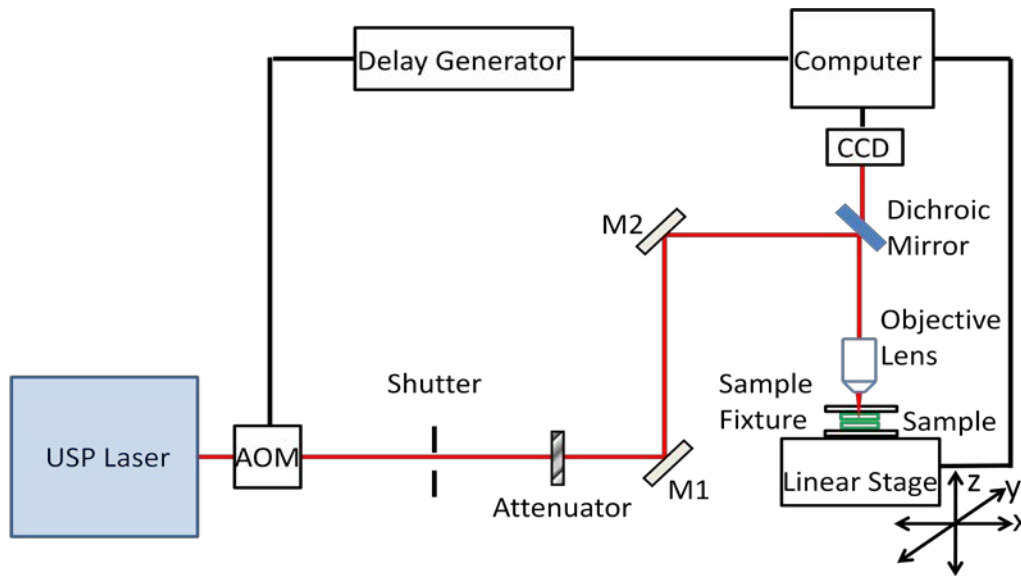


Figure 1. Experimental set up for fs laser welding and sealing of transparent materials

where  $\lambda$  is the laser wavelength and N.A. is the numerical aperture of the objective lens. Two kinds of objective lens were used (N.A. = 0.4 & 0.55) and the focal spot diameters both are less than 5  $\mu\text{m}$ . The total loss of the beam delivery system is less than 50%. Such a loss has been accounted for in the irradiation pulse energy values stated hereafter. An attenuator is used to control the laser pulse energy for fabrication and a mechanical shutter is synchronized with the laser system. A CCD camera is placed along the optical axis and used to align the sample and obtain a live view for the laser processing.

A mechanical sample fixture was used to hold the samples on a motorized translation stage. Furthermore, the sample fixture has two tilt angles adjustments for sample tilting and alignment. The sketch of the sample fixture cross sectional is shown in Fig. 2. Two transparent material substrates are stacked together and a cylindrical lens that creates a pressure region under the bottom plate is placed underneath the bottom substrate. Moderate pressure was applied on both top and bottom plates and close contact was achieved at the interface of the two sample substrates. The laser beam was irradiated from top through the open window of the top plate. A cylindrical lens, or portion of a cylinder, will create a linear pressure region between the two substrates. A cushion material on top of the cylindrical lens was used to extend the pressure area and to keep the pressure uniform over the area. By using an extended pressure region, it is possible to weld longer lengths and subsequently larger total areas, meanwhile it can also prevent the over stressing or fracturing of the bottom substrate. The sample is moving together with the linear stage and the focused laser beam is irradiated from top in transverse direction. The linear motion stage and the delay generator for AOM are controlled by computer to achieve different sample moving speeds and different pulse repetition rates.

## 2.2 Materials

Fused silica has excellent mechanical, electrical, chemical and especially optical properties and is widely used in numerous applications such as optics, telecommunications, electronics, MEMS and biomedicine. In this experiment fused silica (Corning 7980) was used and the samples substrate dimension was 10 mm  $\times$  10 mm, with a thickness of 0.5 or 1 mm. The sample was polished for the main surfaces and the surface roughness of the sample is 2 nm and the flatness is around 1/4 wave per inch across the surface. Before processing, each sample was cleaned by isopropanol.

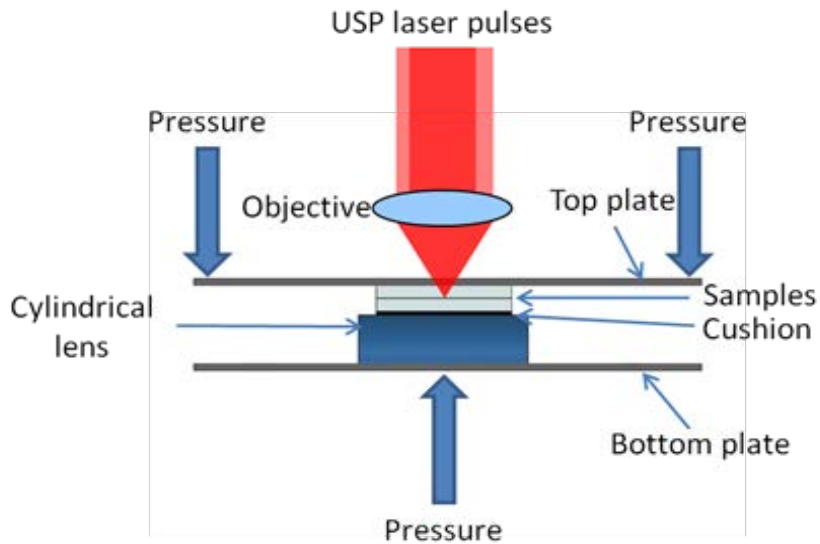


Figure 2. Sketch of cross section of the sample fixture for fs laser welding.

### 2.3 Microscopy & measurements

The micro topography of the modification by fs laser was characterized with an upright digital microscope (ME520T), and the cross section of the modification was checked after polishing both edges. The welding seam and region were checked and measured by a scanning electron microscopy (SEM, FEI QUANTA FEG 600).

## 3. RESULTS & DISCUSSION

### 3.1 Single line welding

For fs laser welding, the laser focus was positioned at the interface between the two fused silica substrates. First of all, single line welding was conducted with different laser parameters. The size and shape of the welded region depend on the laser parameters and the sample translation velocity. To systematically study the fs laser welding, the sample was scanned at different speeds and pulse energies. After processing, the welded samples were broken apart to study and characterize the welded region. Figure 3 shows the microscopic view of single line welding results at the bottom fused silica substrate after broken apart with different welding speeds and the same pulse energy (0.95  $\mu\text{J}$ , N.A.=0.4). Both of the sample dimensions are 10 mmx10 mm with 1.0 mm thickness. The welding speeds are 0.1, 0.2, 0.5, 1.0, 2.0, 5.0 mm/s respectively from top to bottom. It is noted that the welding seams with speeds from 0.5 to 5.0 mm/s are not continuous. This is because there are portion of the seams remained at the top substrate when broken apart. Figure 5 shows the measured single line welding seams widths for different welding speeds shown in Fig.3. As shown in Fig. 4, the single line welding seam width is decreasing from 5.6  $\mu\text{m}$  to 2.6  $\mu\text{m}$  when the welding speed is increasing from 0.1 mm/s to 10 mm/s. Although the weld line width becomes smaller for larger scanning speeds, the welding seam is still kept uniform. High speed welding and sealing makes the welding technique applicable for industrial applications. The welding seam width and strength can be compensated by using higher pulse energy or higher repetition rates.

Since the repetition rate is high and there are hundreds of thousands of pulses hitting at the same spot, a useful measurement of exposure is the average fluence  $F_{ave}$  along the writing path and it can be defined by Eq. (2):

$$F_{ave} = \frac{E * R}{D * v} \quad (2)$$

Where E is the single pulse energy, R is the repetition rate and v is the laser writing speed. For all the single line welding results as shown in Fig.3, the average fluences used in Fig. 3 are 1979  $\text{kJ}/\text{cm}^2$ , 990  $\text{kJ}/\text{cm}^2$ , 396  $\text{kJ}/\text{cm}^2$ , 197.9  $\text{kJ}/\text{cm}^2$ , 99.0  $\text{kJ}/\text{cm}^2$ , 39.6  $\text{kJ}/\text{cm}^2$  respectively from top to bottom.

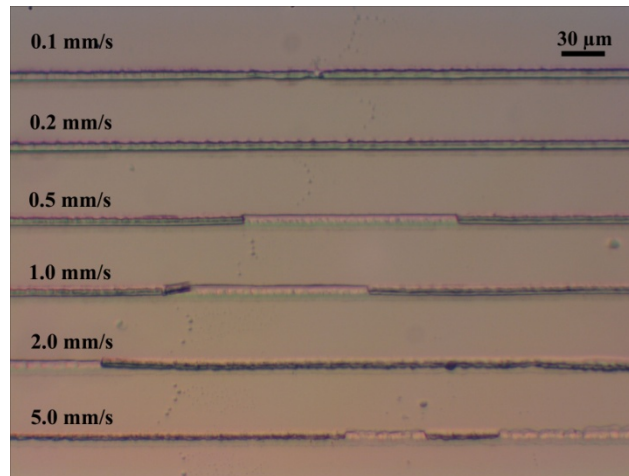


Figure 3. Microscopic view of single line welding at the bottom fused silica substrate with different scanning speeds and the same pulse energy (0.95  $\mu\text{J}$ ).

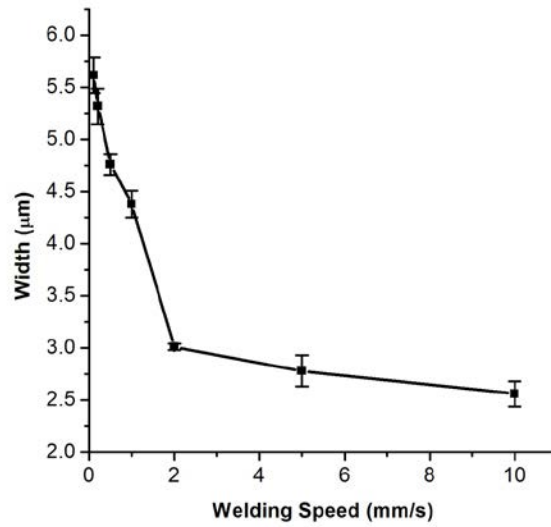
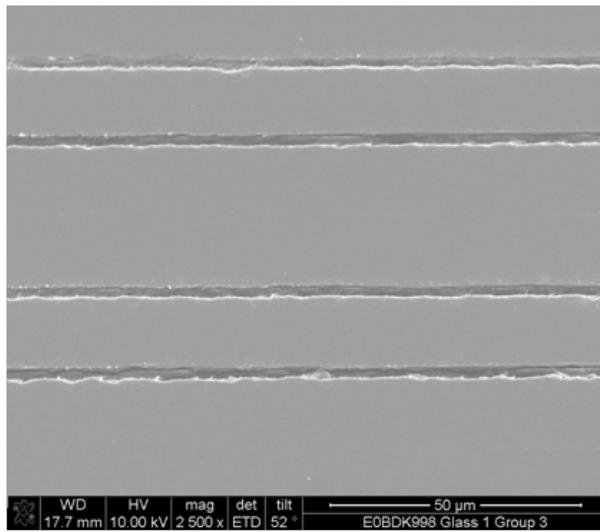
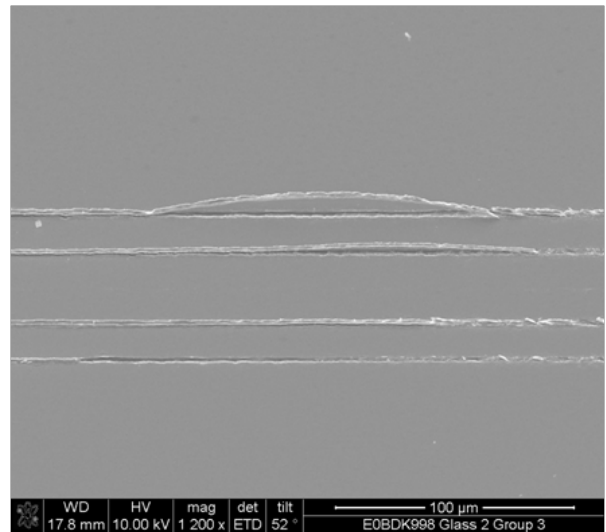


Figure 4. Single line welding widths for different welding speeds and the same pulse energy (0.95  $\mu\text{J}$ ).

Figure 5 shows SEM tilted angle view of single line welding of another set of fused silica substrates after broken apart. Both of the sample dimensions are 10 mmx10 mm with 0.5 mm thickness. The welding speed is 1 mm/s and the average fluence used here is 26.5  $\text{kJ}/\text{cm}^2$ . Figure 5(a) shows the welding surface of the top substrate showing grooves – the welding seam peeled off, and Fig. 5(b) shows the welding surface of the bottom substrate showing bumps – welding seam remains. So the welding seam for single line can be clearly seen and most of the welding seam remains on the bottom substrate since the bottom substrate is fixed and the top substrate is peeled off manually.



(a)



(b)

Figure 5. SEM tilted angle view of single line welding of fused silica after broken apart ( $F_{\text{ave}}=26.5 \text{ kJ}/\text{cm}^2$ ): (a) the welding surface of the top substrate showing grooves– welding seam peeled off; and (b) the welding surface of the bottom substrate showing bumps– welding seam remains.

### 3.2 Multi line welding

After single line welding experiment, multi line welding experiments with space were also investigated to obtain large welding area. Figure 6 illustrates laser glass multi line welding results. Both of the sample substrates dimensions are 10 mmx10 mm with 1 mm thick. The welded line starts from one edge of the sample to the end of the other edge and each of the welding lines is 10 mm long. From the camera picture as shown in Fig. 6, there is clearly a rectangular section (black rectangular region) that does not show any interference fringe all the way along the sample from left to right. This shows very good complete one edge sealing along the whole length. For the welded region, there are totally two welded area sections and each section is about 500  $\mu\text{m}$  wide with 5  $\mu\text{m}$  pitches and the welding speed is 1 mm/s. From top to bottom, the first section is two times repeated scanned average fluence of 37.4  $\text{kJ}/\text{cm}^2$  and 10  $\mu\text{m}$  focal position change – the sample moves towards the laser beam; the second section is scanned with average fluence of 27.0  $\text{kJ}/\text{cm}^2$  and three times repeat scan with 10  $\mu\text{m}$  focal position change for each repeat. The total number of lines for the two area scanning is 200 and the total welded area size is 10  $\text{mm}^2$ .

Figure 7 illustrates how the glass substrates are bonded together after fs laser multi line welding. When holding the top glass by tweezers, the bottom glass is bonded together with top glass sample.

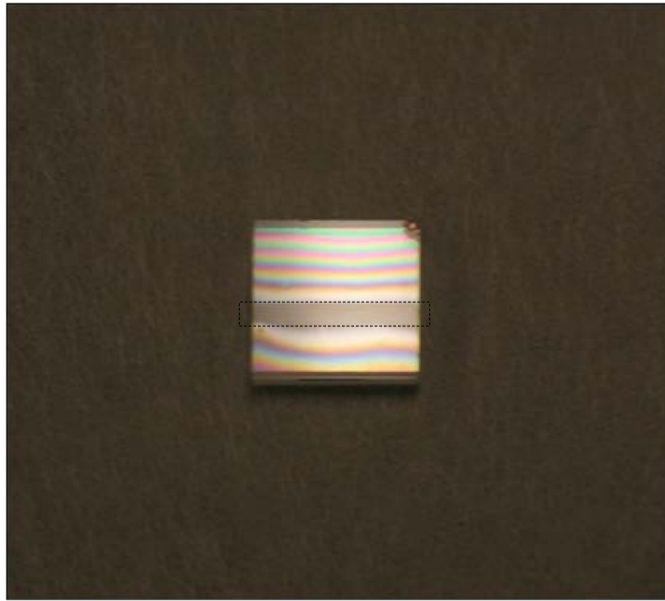


Figure 6. Camera top view of fused silica substrates after fs laser multi line welding.

### 3.3 Sealing of fused silica

After the multi line welding experiment, it can be further applied to seal a complete region by using four-edge multi line welding so that we can protect the center region with or without optical coating on the surface. Two fused silica sample substrates without optical coating were used to give a proof of concept demonstration. Figure 8 shows illustrations of four-edge sealing of two fused silica samples with fs laser, where Fig. 8(a) shows the top view with interference fringe seen for those non-welded regions and no interference fringe seen for those sealing seams, and Fig. 8(b) shows transmission view of the four welding seams crossing with each other with LED backlight illumination. Both of the sample dimensions are 10 mmx10 mm with 1.0 mm thickness. The welding speed is 1 mm/s and the average fluence used here is 26.5  $\text{kJ}/\text{cm}^2$ . Three times repeat scanning with 10  $\mu\text{m}$  focal position change was used. For each sealing edge, the welded region area is 250  $\mu\text{m}$  wide, so the welded seam area size is 2.5  $\text{mm}^2$  and the total welded area size for four edges is 10  $\text{mm}^2$ .

Furthermore, to further show the hermetic sealing of the two substrates, one corner of the sealed sample was immersed in to water to see whether water can penetrate the sealing seam or not. Figure 9 illustrates how the center region is well



sealed by fs laser for a square shape sealing and water immersion from the top-left corner cannot penetrate into the center region due to the block of the surrounding sealing seams. The purpose of the sealing may not only be to contain a liquid, but can also be used to seal against gas. Additionally, the bottom surface of the top glass substrate or the top surface of the bottom substrate may have coatings that are protected by the welding of a hermetically sealed region. The coating can be on one or both of the slides. The substrates can comprise any optically transparent substrate or filter that has a coating that needs to be protected from the environment. This enables the sealing of filters with coatings and even multi-layer three dimensional sealing of optically transparent materials for a variety of industrial applications.

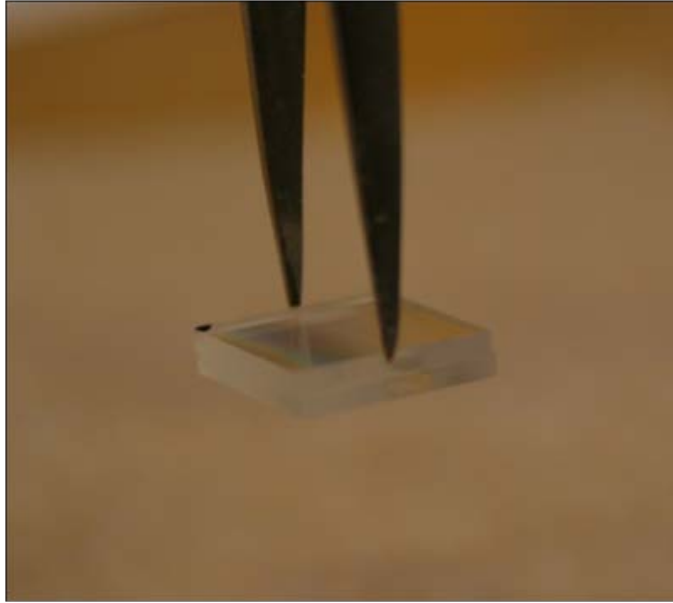
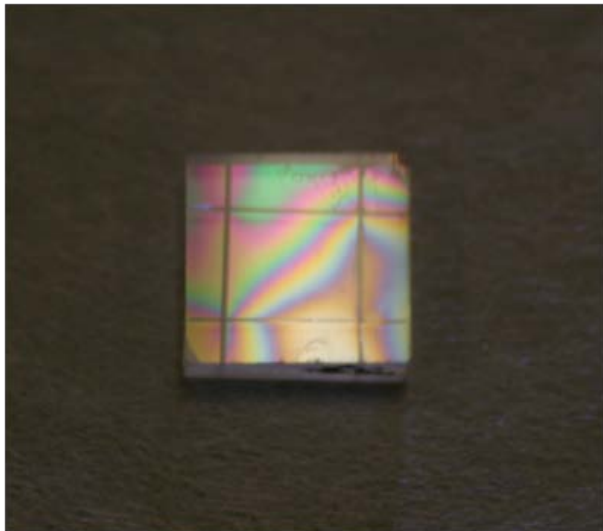
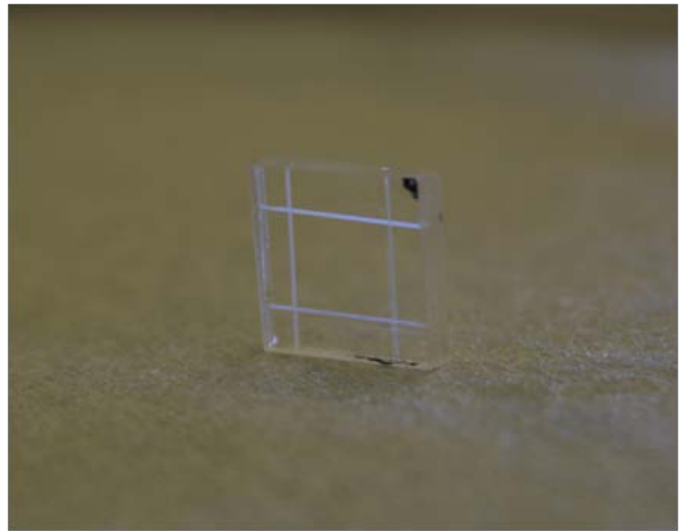


Figure 7. Camera view of welded fused silica substrates bonded together by fs laser



(a)



(b)

Figure 8. Fs laser four-edge-sealing of fused silica samples ( $F_{ave}=26.5 \text{ kJ/cm}^2$ ): (a) top view with interference fringe seen for non-welded region and no interference fringe seen for sealing seams; and (b) transmission view of the four welding seams crossing with each other with LED backlight illumination.

Water immersion region

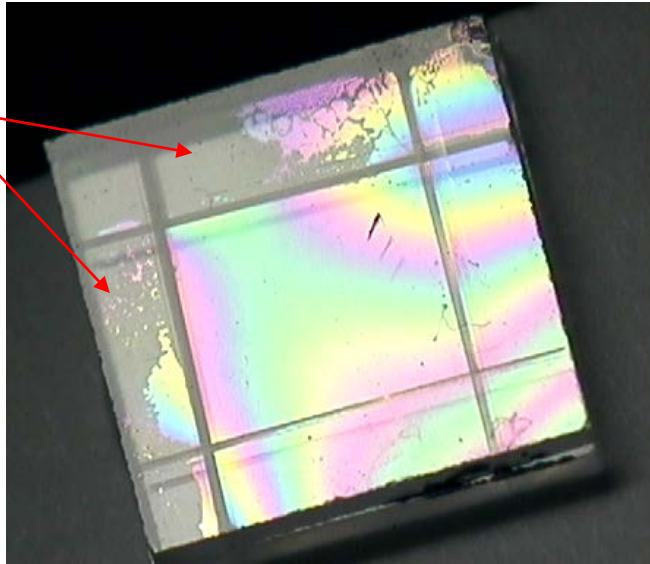


Figure 9. Camera view of the center region well sealed by fs laser - water immersion from top-left corner cannot penetrate into the center region due to the block of sealed edges.

#### 4. SUMMARY

In conclusion, welding and sealing of fused silica using fs fiber laser were demonstrated. Welding of two fused silica substrates with different thicknesses were performed with different laser parameters and the welding seams were characterized. To demonstrate proof of concept, complete four-edge sealing of fused silica with fs laser repeat scanning was conducted. This work overcomes this limitation of small area welding and demonstrates the capability to weld and seal fused silica using fs lasers of area of  $10 \text{ mm}^2$ . This fs fiber laser based process is inherently simple, direct, reliable and reasonably inexpensive. This commercial laser system is more attractive as compared with fs solid state lasers. This shows the capability to weld similar and dissimilar materials using fs lasers over large area and increases the potential for fs laser welding and sealing applications in semiconductor industry, precision optic manufacturing and aerospace engineering using fs lasers.

#### ACKNOWLEDGE

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